BASIC CHARACTERISTICS OF NUCLEAR RADIATION FROM FALLOUT 1.2

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Definition of the Terminology

Fallout is of considerable interest in radiation protection problems because many nuclear processes of short time duration such as nuclear weapon detonations and nuclear reactor excursions cause radioactive debris to be thrown into the air, ultimately to settle into an area different from that at which the nuclear process occurred. In the strictest sense the word fallout is technically correct only if used to refer to debris that has been deposited on the earth after being airborne, but in current practise the word is used interchangeably to refer both to particulate matter that is aloft and to matter that has been deposited on the surface of the earth. Depending on the conditions of formation, fallout from nuclear weapon detonations ranges in texture from an aerosol to granules of considerable size. The aerodynamic principles governing its deposition are the same as for any other material of comparable physical nature that is thrown into the air, such as volcanic ash or particles from chimneys. However, the radioactivity found in fallout produced by processes involving nuclear fission and nuclear fusion has caused the public generally to associate the name fallout only with this particular type of deposited debris. This very special usage of the word fallout is continued in this review in which, with or without any modifying clause, it refers only to the airborne or deposited debris produced by nuclear processes of short time duration, primarily nuclear weapon detonations.

Ionizing Radiations Resulting from a Nuclear Weapon Detonation

If a weapon depends on fission to develop its energy, radiations consisting of neutrons, beta particles, and gamma rays can be expected. Neutrons are boiled off immediately after the fission fragments are formed and possess an energy spectrum that can be approximated by a Maxwellian-type distribution.[1,2] Following neutron emission most fission fragments undergo further deexcitation by emission of gamma rays. Most of the prompt photons result from a deexcitation process with a half life of about 10^{-11} seconds,[3] but a small component (about 5.7%) is delayed, with a half life of about 10^{-7} seconds,[4] and a few continue to be emitted at an observable and steadily decaying rate for times as long as 10^{-3} seconds after fission.[5,6] Because they are released in so short a time, neither prompt neutrons nor prompt gamma rays are ever a part of a fallout radiation field. They, therefore, are not considered further in this discussion. However, considerable quantities of information about them are available.[7]

The nuclear fragments that remain after release of the prompt radiations still are not stable, but contain an excess of neutrons. To reach stability they undergo beta decay, which is accompanied by gamma radiation[5] that can be used to measure many characteristics of the beta-decay process following fission, and even a few delayed neutrons.[8] The half-lives of the radioactive nuclei are of course those associated with the beta-decay processes and depend on the transition energy, which is related to the magnitude of the neutron excess (sometimes called the distance from the line of stability).

About 10^{-3} second after fission the rate of emission of prompt radiations becomes sufficiently small to be unobservable. A reasonably constant rate of decay of beta-decay-produced gamma rays is then found until about 10^{-1} second after fission. After this time enough fragments have undergone beta decay to cause a general shift of the fragment population toward the line of stability, with the result that the average energy of decay is lowered and the average half-life lengthened. As a consequence, a continuing decrease in the rate of emission of ionizing radiation occurs after the initial relatively constant rate. A theoretical basis for this type of decay was first established by Way and Wigner.[9] They determined that the rate of radiation emission at early time t should be described by an equation of the form $a - bt$, where a and b are constants, but after several minutes the rate of emission of radiation can best be described by a single $t^{-1.2}$ term. Such a time-dependent law to describe the decay of fission-induced radioactivity has been found from experiments to be generally valid, but to have many differences in detail,[10] as observed in the experimental results of neutron-induced fission[5,10] of ^{235}U and of photon-induced fission[6] of ^{235}U and ^{232}Th.

Fisher and Engle[11] have measured the spectral characteristics and relative intensities of the fission-product gamma rays at selected times between 0.2 second and 45 seconds following fast-neutron fission of a number of nuclides and Peelle et al.[12] at times between 1.7 seconds and 1500 seconds following thermal-neutron fission of ^{235}U. Bunney and Sam[13] overlap and extend to three days the work by Peelle et al. in their measurements of the spectra of gamma radiations emitted by the fission fragments following fast-neutron fission of ^{235}U and ^{238}U. The results found by Bunney and Sam are in reasonably good agreement with those of Peelle et al. in the overlapping time interval of 15 to 16 minutes following fission. Peelle et al. find that the intensity of the fission-product radiation, measured as photons MeV^{-1} $fission^{-1}$ sec^{-1}, at 200 seconds after fission is about 1/100 the intensity at 1.7 seconds after fission, in general agreement with predictions. Fisher and Engle's results also indicate that the rates of decay agree with theory.[5] Thus more than 99% of the fission-product gamma rays are emitted within the first three minutes following fission. Since the radioactive material is still distributed within a mushroom cloud at three minutes after a near-surface burst of a nuclear weapon, none of the ionizing nuclear radiations emitted by the fission fragments prior to that time can ever appear to be emitted by the fallout from the burst. Because of the time required for radioactive debris to begin to be distributed in significant quantities, only those radiations emitted by fission products more than several minutes old are significant in the fallout problem. Thus, only a very small fraction of 1% of all the fission-product photons will ever appear as fallout radiation, the exact amount depending on the time required for the radioactive debris to settle to the earth in the vicinity of the detonation.

Calculations have been made[14,15] of the gamma-radiation spectra from fission-product radioactive nuclides for times ranging from a few minutes to several years after slow-neutron fission of ^{235}U, based on fission-yield calculations of Bolles and Ballou.[16]

Radioactivity may also be produced by neutron interactions within the weapon itself. In many weapons the primary radiation of this type is ^{239}Np (half-life, 2.3 days) produced by the reaction $^{238}U(n,\gamma)$ $^{239}U(\beta)$ ^{239}Np because of the presence of ^{238}U (see pp. 1690-91 of reference 17). The nuclide ^{239}U decays with a half-life of only 23.5 minutes so usually is not observed in significant amounts in fallout measurements.

Other materials besides uranium can be introduced into the regions surrounding the active portions of a nuclear weapon. These materials are then subjected to a tremendous neutron flux density when the weapon is detonated, with the result that many radioactive nuclei are formed. At one time the hazards produced by gamma radiations of a so-called cobalt bomb were discussed extensively. Based on what he considered reasonable assumptions, Dunning[18] calculated the residual-radiation exposure and exposure rate that one could expect from a one megaton nuclear weapon, containing cobalt, that derived half of its energy from fission and half from fusion. His conclusions are that the effect of the cobalt is almost insignificant at very early times but it becomes appreciable after several days. For example, his calculations indicate that one hour after detonation the gamma-ray exposure rate produced by the fission products is about 5.9×10^5 times the exposure rate produced by the ^{60}Co gamma rays, but after 30 days the fission-product exposure rate is only 0.02 times the ^{60}Co exposure rate. An infinite time extrapolation shows the contribution to the total-exposure by fission-product radiations and by ^{60}Co radiations to be approximately equal. Radiations emitted by long-lived neutron-induced activities, such as those from ^{60}Co, are delayed considerably compared to fission-product radiations. For example, almost 100% of all photons emitted by a source of ^{60}Co are emitted more than three minutes after the source is produced. As a result, the percentage of the total radiation hazard associated with fallout from a detonation of this type would be much greater than from a detonation in which the only sources of residual radiations are the fission-product radioactive nuclides.

The technical possibility also exists that all neutron-induced activities are short-lived, such that the overall effect is opposite to that described for ^{60}Co, and would lead to greatly reduced amounts of long term radioactivity in any fallout that is produced. A significant reduction per kiloton of weapon yield is also found in the long-lived radioactivities of local fallout if a nuclear weapon has a sufficiently high fusion/fission ratio.

Comparison of Fallout and Fission Product Gamma-Ray Spectra

Cook[19] has compared calculations by Nelms and Cooper[15] of expected gamma-radiation spectra from radioactive fission-product nuclides with measured gamma-ray spectra of fallout samples. These comparisons indicate that there is a reasonably close resemblance between calculation and experiment for photons with energies greater than 290 keV. However, the ^{239}Np radiations in the experimental measurements usually completely

obliterate the fission-product radiations in the energy regions between 100 and 290 keV. Differing amounts of ^{239}Np in the radioactive products of different weapons produces uncertainties in the comparison. Furthermore, fractionation, briefly discussed in a later section of this paper, greatly reduces the accuracy with which exact spectral characteristics of sources of fallout gamma radiation can be predicted.

Aerodynamic Effects

Many observed characteristics of the ionizing radiations emitted by deposited nuclear weapon debris are dependent on the way in which the debris is distributed. The detailed nature of this distribution depends on existing air currents, height of burst, weather pattern, and many other factors. After deposition, debris particles may be further moved in varying amounts, depending on the nature of the particles themselves, as well as the characteristics of the ground surface, air currents, rainfall, and other factors.

Because of the rapid expansion of the air near the point of detonation and the consequent lowering of air density, a large percentage of the material associated with the detonation is carried into a cloud having the general shape of an oblate spheroid. This cloud usually reaches a height of several thousand feet above the point of detonation if the detonation occurs reasonably close to the surface of the earth. If all particles in the cloud are assumed to be about the same shape and of constant density, the time required for them to reach the surface of the earth from some given height is a function only of particle size, the larger particles being the first to reach the surface.[20] Furthermore, if there is a prevailing horizontal shearing wind pattern to carry away particulate matter, the larger-diameter (larger-mass) particles are deposited closer to the point of detonation than the smaller-diameter particles. Because of the finite size of the cloud formed by a weapon detonation and the general distribution of particles throughout the cloud, as well as the various possible routes that a falling particle can take in returning to the surface of the earth, a range of particle sizes is found at any point downwind from a nuclear detonation. As a result, the distribution of fallout particulate matter from the cloud is roughly divided into three topographical categories called local (or close-in), tropospheric (or intermediate), and stratospheric (or world-wide) fallout.

Local fallout consists of the larger particles (often defined as those with diameters greater than 20 microns) which, because of their size, have a high rate of settling and fall within approximately 100 miles of the point of detonation. After the tremendous energy of the explosion has been dissipated, these particles fall reasonably quickly, carrying with them much of the radioactivity. Because of the large range of particle sizes in the cloud produced by a nuclear weapon detonation, and the prevailing horizontal shearing wind patterns that exist in most of the earth's atmosphere, elongated local fallout patterns are usually formed following near-surface bursts.[21-24] These regions of local fallout can usually be found by observing the gamma-radiation associated with them, such as the gamma-ray intensity contours shown in frames F through I of Fig. 1 for a 1 kt near-surface burst.[39]

Tropospheric fallout consists of particles injected below the tropopause that are a few microns in diameter or smaller. These particles continually mix through the circulating air mass of the earth and gradually settle to the ground or are brought down by rain or snow.[25-27] Parts of the tropospheric fallout may remain in the atmosphere a month or more, long enough to circle the earth several times. Stratospheric fallout consists of particles similar to those in the tropospheric fallout but which has been injected into the region above the tropopause. This material has a mean residence time of many months, for some nuclides as much as a few years, during which time it completely encircles the earth. It gradually returns through the tropopause, primarily in certain regions where mixing between the two layers is more probable than in others. In this symposium we are concerned only with problems of local fallout, so only occasionally will any further reference be made to either tropospheric or stratospheric fallout.

Detonation Conditions Needed to Form Local Fallout

Large amounts of radioactive fallout occur locally only if large quantities of material are present onto which radioactive nuclides produced by the weapon can be attached. If a weapon is detonated within a few hundred feet of a land surface, the explosion causes soil and other particles to be introduced into the fireball before condensation of the vaporized material is complete. Condensation then takes place either directly onto the surfaces of the hot oxide or silicate particles from the earth, or by a two-step process in which the vaporized materials first condense and then impact and collect onto the earth-surface materials.[28] Following an air burst, unvaporized surface materials onto which radioactive weapon debris can condense are generally absent from the fireball. The weapon radioactive debris can then combine only with naturally occurring aerosols, and is carried away as extremely tiny particles, or as gas molecules, to form only tropospheric or stratospheric fallout, except possibly in a rain-producing atmospheric region,[27] when the probability of precipitation of reasonably large quantities of radioactive debris in localized areas appears to be relatively high. If a weapon detonation takes place sufficiently far below the surface, local fallout is again absent because the radioactive materials are trapped by the surrounding earth. Thus the amount of local fallout depends on the height or depth of the detonation, as well as the weapon yield and the nature of the terrain.[29,30] The fraction of the total radioactivity going into local fallout, tropospheric and stratospheric fallout and trapped within the earth has been plotted (Fig. 2) by Nordyke[29] as a function of the ratio of the depth of burst to the depth of apparent crater for alluvium at the Nevada Test Site. A negative ratio means that the burst is above ground. He uses the word prompt to refer to local fallout and long-range airborne to refer to the combined tropospheric and stratospheric contribution.

Fractionation

Radiochemical analyses performed by Mackin et al.[31] on individual fallout particles from a nuclear detonation at Bikini Atoll indicate that prediction of the radiation characteristics of fallout may not be

particularly simple. Such radiochemical analyses are strongly influenced by fractionation, a term used to describe any alteration occurring between the time of detonation and the time of radiochemical analysis. Fractionation causes the radionuclide composition of a debris sample to be non-representative of the detonation products as a whole.[32,33] This process begins with the condensation of radioactive and inert material from the fireball, some radionuclides being preferentially taken up by the condensed phase. Although the chemistry of fractionation in nuclear weapon detonations is not itself a part of the problem of the ionizing radiations, the fractionation process can play a profound role in determining the types and energies of the radiations that are observed following nuclear explosions. For example, Mamuro et al.[34] note that particles enriched in ^{95}Zr + ^{95}Nb and in ^{140}Ba + ^{140}La, but impoverished in ^{103}Ru have been found in fractionated fallout from nuclear test explosions by the U.S.A., U.S.S.R., and China, but particles impoverished in ^{140}Ba + ^{140}La are not found in U.S.S.R. fallout, although such particles are found in U.S.A. and Chinese fallout. This effect is probably related to the conditions of detonation. A survey of the physical and radiochemical properties of fallout particles has been given by Crocker et al.[35]

For underwater detonations a bubble of intensely hot gases and water vapor is formed. This bubble usually breaks through the surface and its contents are distributed by the prevailing winds. Following a detonation of a device on a barge anchored in the lagoon at Bikini Atoll in water sufficiently deep that little or no material from the lagoon bottom was swept up into the fireball, Adams et al.[28] found that evaporated seawater did not condense until very low temperatures had been reached, such that the amount of condensation or vaporized solids was about the same as after an air burst.

Neutron-Induced Activities in Surrounding Materials

Besides those that are fission products, other radioactive nuclides are also formed by neutron capture in materials within a few hundred feet of the point of detonation. Radioactive nuclides produced in soil below an air burst form a gamma-radiation field in a nearly symmetrical pattern around surface zero, as illustrated in Fig. 1 (A through E) for a 1 kt air burst.[36] Generally this radiation field decays relatively rapidly because its longest-lived radionuclide, ^{24}Na, has a half-life of only 15 hours. Other radionuclides usually found in reasonable abundance are ^{56}Mn and ^{28}Al. The magnitudes of these gamma-radiation fields not only vary considerably for soils having differing chemical content but also depend on the moisture content of the soil.[7]

The effect of relative height of burst on the distribution of residual radioactivity is seen rather dramatically in Fig. 1 in which the radiation field contours of a near-surface burst, even though produced by a smaller yield device, cover a much larger area and decay much more slowly than the radiation field of an air burst, because fission-product radioactivity results from many more and longer lived radionuclides than the radioactivity induced in soils by neutrons of an air burst. However, Batzel [37] has indicated that, if a purely fission weapon were detonated underground, the neutron-induced activities one day after detonation can be as much as 25% of the total activity, as illustrated in Fig. 3, but this relative activity drops to about 1% after one week

and 0.1% after 1-1/2 months. If the detonation is above ground, the contributions from neutron-induced activity are smaller because of the smaller solid angle of earth subtended for the incident neutrons. The ratio of fission-product activity to neutron-induced activity is thus strongly dependent on detonation conditions. Neutron-induced activities in surrounding media for weapon detonations near the ocean surface are indicated by Heiman[38] to be less significant than for those near land surfaces.

Gamma Radiation from Distributed Sources

Because fallout particles from near-surface nuclear detonations are usually deposited over a reasonably large area downwind from the point of detonation, knowledge of the radiation fields produced by distributed sources is important in any consideration of the effects of fallout. For calculational purposes an ideal distributed source would be planar, of infinite extent in the direction of the plane, uniformly distributed and infinitesimally thin. In reality, however, the distribution is seldom very uniform. Furtherfore, wind and rain cause the fallout particles to settle into intersticial regions of the ground surface because most exposed soil surfaces are usually relatively rough. These particles are often covered by dust or blocked from view by the numerous minute vertical projections of the surface. The result is that ionizing effects from beta radiation extends, at most, to a few centimeters above the surface, and often not even that high. The gamma radiations emitted by the radioactive particles are modified by the attenuation properties of the intervening earth and air between source and detector. The characteristics of the radiation above such a distribution of radioactive source material are thus a combination of scattered and direct gamma radiation. If the interstices on the earth's surface are small, relatively close together and randomly spaced, a gross investigation of a few square meters of surface area should reveal an apparent uniform distribution of radioactive fallout particles, even though a microinvestigation reveals quite large non-uniformities.

To arrive at a realistic estimate of the dosimetric effects of a distributed source of fallout particles has required a series of different types of calculations and experiments, some of which are reviewed in the following paragraphs.

Calculated Radiation Fields

Measurements and calculations mentioned earlier in this paper have been concerned primarily with the basic physical characteristics of the gamma-radiation from fallout, such as number or photon spectra and generally with good-geometry measurements. On the other hand, radiation hazard from fallout must be related to exposure spectra, which indicate the exposure rate (air ionization per unit time) associated with the photons in each energy interval. Also the radiation is incident on a subject from a number of directions, not a good-geometry situation. Two steps are necessary to relate photon spectra to exposure spectra. First, an energy spectrum, which gives the total energy of all photons emitted per unit time within each energy interval, must be derived by multiplication of the number spectrum and the mean energy of each energy interval.

Next, to derive the exposure spectrum, the energy spectrum is multiplied by the energy absorption coefficient for air for each energy interval. Finally, both the effect of the absorbing material between source and detector, as well as the physical distribution of the source must be considered. In fallout applications the source is generally considered to be planar and the detector to be about 3 feet (approx. 1 meter) above the plane of the source.

A number of calculations have been made of the radiation field produced in air above a planar, infinitesimally-thin gamma-ray source, both for sources of infinite extent and for sources having specific geometrical shapes, such as rectangular or circular plaques. These calculations for surfaces of specific shape and size have usually been made to assist people engaged in shielding research who must consider situations in which there is fallout on areas of finite size, such as building roofs and areas between buildings. Most calculations are useful only for determining the radiation field to be expected in specific geometrical arrangements and each problem must be solved individually. A comprehensive documentation of work of this type is given in reference 39.

Crocker et al.[40,41] have calculated what they call exposure-rate factors for gamma-ray emitting radionuclides produced by fission of uranium and plutonium, as well as comparable factors for a number of neutron-induced radioactivities that are sometimes found in weapon debris. This factor, expressed in units of [R/hr] / [(disintegrations/sec)/cm^2], is derived for an exposure-rate in air three feet above the idealized situation of a non-absorbing plane of infinite extent uniformly contaminated with the nuclide in question, emitting radiation at the rate of one photon per second per cm^2 of contaminated plane. In Appendix III of reference 42, Taylor estimates that 1.0 μCi/cm^2 of fallout radioactivity on an infinitestimally thin, planar surface gives an exposure rate of approximately 0.1R/hr three feet above the surface. This rate corresponds to an exposure-rate factor of 2.7×10^{-6}, which is in reasonably good agreement with an appropriate mixture of the exposure-rate factors of the various radionuclides considered by Crocker et al. Those radionuclides that emit higher energy photons, such as ^{140}La, have larger exposure-rate factors, which means that smaller amounts of these radionuclides are required to produce the same exposure rate. Using their earlier experimentally determined fission-product spectra[13] Bunney and Sam have calculated[43] the exposure rate three feet above a smooth plane uniformly contaminated with unfractionated products of the fast-neutron fission of ^{235}U. Their results are shown in Fig. 4. Comparisons with calculations using the results of Crocker and Turner[41] indicate that, for photons between 0.7 and 4.0 MeV, the two techniques give results differing by less than 1% on the average and less than 8% for specific photon energies.

For the distributed source problem, Spencer[44] has calculated the gamma-ray dose arriving within a small increment of solid angle at a detector in an infinite air medium above a plane source of infinite extent. The results of his calculations as a function of radiation angle of incidence and height of the detector above the source plane are shown in Fig. 5. Other calculations of the angular distribution of multiply scattered gamma radiation have been made by Berger.[45] French[46] has calculated the gamma-radiation environment three feet above a distributed source on a smooth ground surface by using Monte Carlo techniques.

In addition to air scatter, a problem also exists regarding the effect of the air-earth interface on any measurements that are made reasonably close to the surface of the earth. Berger[47] has calculated the expected energy dissipation because of the presence of the air-earth interface, for sources at the surface and at a height $\mu_0 h = 0.5$, μ_0 being the narrow-beam attenuation coefficient in air of the source radiation. The energy of the primary radiation used by Berger in his calculations was 1.28 MeV. He concluded that (1) there is an increase of energy dissipation near the source, and a decrease far from the source, in such a manner that the total dissipation in a layer of given mass, parallel to the density-interface, is constant; (2) the increase is relatively small, not more than 20%; (3) with increasing source-detector distance, the decrease of energy dissipation of the interface compared to that in an infinite medium becomes more pronounced and tends toward 100%; and (4) the farther the detector is from the source, the greater the distance from the density-interface at which the perturbation is still noticeable.

Eisenhauer[48] discusses problems of the effects of ground roughness on the measured dose in air above a fallout source distributed on the ground. Effects of attenuation by the earth of radiation originating in crevices and depressions most commonly are approximated by a model that assumes that an infinitesimally thin planar source is buried beneath a given thickness of soil.[49] A variation of this model assumes the characteristics of the observed radiation to be equivalent to measurements made at some greater height $(h + 3)$ feet above a smooth infinitesimally thin source of radiation.[47] The effect of the intervening earth is then treated as an equivalent amount of air. In at least one case[50] calculations were made in which the source material was assumed to be uniformly distributed through a layer of earth just below the air-earth interface.

Experiments Using Simulated Sources

Gamma radiation fields of deposited fallout have been simulated experimentally by spreading one or more gamma-ray emitting radionuclides over a flat area. An example is the work of Davis and Reinhardt[51] who simulated a fallout radiation field by means of plane rectangular arrays of ^{137}Cs and ^{60}Co sources. Individual sources in each array were 100 feet apart and the entire array covered an area 2000 feet on a side. The results were calibrated through use of point sources of ^{60}Co, ^{131}I, and ^{137}Cs. Davis and Reinhardt conclude that the use of a buildup factor for which the highest term is only a first power of μh is in relatively good agreement with experimental observations. This they conclude by showing that the buildup factors are approximately a linear function of height in the equation $B(\mu h) = 1 + a(\mu h) + b(\mu h)^2 + \ldots$ for radiation from point sources. The magnitude of the coefficient a is larger for lower than for higher energy gamma radiations. Based on comparisons of their experimental results with calculations, Davis and Reinhardt conclude that an array of the type they used that is 2000 feet on a side is sufficiently large to simulate a uniform source of infinite area for measurements near the ground, but is inadequate for measurements of the ^{60}Co radiations at 500 feet altitude or higher.

In the spectral measurements by Davis and Reinhardt, a pronounced increase of low energy photons was observed in the measurements farther from the ground. These results give evidence of scattered radiation at those heights. More explicit information about the angular distribution of scattered radiation at a distance from a point source has been obtained from experimental measurements by Sakharov et al.,[52] whose measurements have indicated that, at distances from the source in excess of 150 meters, the angular distribution of scattered radiation at the detector is almost independent of the distance from the source. There appears to have been no attempt to correlate this work on the scattering of gamma rays with the results of Berger's[47] calculations. On the other hand, Clifford et al.[53] have experimentally measured gamma-radiation intensities at selected distances from a ^{137}Cs source located on a smooth clay surface and compared their results with Berger's work. They have determined the ratios of the intensities for this type of experimental arrangement to those obtained at comparable positions when the source is in a homogeneous air medium. Although the energy of the gamma radiation from ^{137}Cs is only 662 keV, Clifford et al. reasoned that both 662 keV and 1.28 MeV, the energy for which Berger[47] made his calculations, are in the energy region of Compton scatter for low and medium Z materials. Apparently their reasoning was correct for they found general agreement with the calculations by Berger.[47] Berger's type of calculation seems then to be applicable to other similar situations over a range of energies. Titus[54] has made similar measurements with a source at the interface between steel wool and steel, and reported good agreement with Berger's calculations. Titus' source was ^{60}Co. Subsequently, Clifford[55] found from use of distributed ^{137}Cs sources that ground roughness greatly reduced the dose received by a detector near ground level compared to the dose received from the same density of contamination on a smooth plane. Furthermore, he concluded that use in calculations of dose of an equivalent thickness of air rather than earth between source and detector causes an overestimate of the dose at low detector heights, at least for ^{137}Cs radiation.

Experiments Using Real Fallout Fields

Mather et al.,[56] Huddleston et al.,[57] and Frank[58] have measured the gamma radiation emitted by fallout that resulted from two near-surface bursts at the Nevada Test Site. All three groups used scintillation spectrometers, with NaI(Tl) detectors, to measure pulse height distributions. Mather et al. and Frank converted their results to photon energy spectra, and Huddleston et al. converted to units of incremental dose.

The detecting systems used by all three research groups were shielded in such a way that the incident radiation was directed into the detector through a collimator having a fixed aperture (solid angle of constant magnitude). If source material is uniformly distributed over a plane of infinite horizontal extent, the field of view through a collimator located above this plane is an amount of source material proportional to $(\cos \theta)^{-1}$, where θ is the angle in a vertical plane between the nadir and the axis of the collimator aperture. If the detector were able to record all source radiation in its field of view (no scattering or absorption), an infinite amount of radiation would enter as the collimator asymptotically approaches $\theta = 90^{\circ}$ and no radiation would enter if $\theta > 90^{\circ}$. Because ground and air molecules both

scatter and absorb gamma radiation, the air and earth intervening between source and detector attenuate the direct radiation, thus the maximum amount of radiation per unit solid angle that enters the collimator is finite, usually at an angle θ just slightly less than 90°. Some radiation, after being scattered by air molecules, also reaches the detector from angles for which $\theta > 90^\circ$.

A set of gamma-ray intensities as a function of angle of incidence is shown in Fig. 6* for four selected energy intervals of the nine-day old fallout that produced the radiation patterns of Fig. 1 (F through I). The measurements of Fig. 6 were made by Mather et al. at a point about 2.5 km downwind from ground zero in a radiation field of about 300 mR/hr. The surface texture was quite coarse, being primarily gravel. Plot A shows the directional characteristics of incident radiation measured in an energy interval encompassing the relatively intense 1.6 MeV photons emitted by the fission product, ^{140}La. The energy intervals encompassed by plots B and C are limited to much weaker source radiations than plot A, and the energy interval of plot D contains essentially no source radiation. The latter must then consist entirely of scattered radiation. Differences between scattered and direct gamma radiations are also quite apparent in the measured spectral characteristics of the radiation directionally incident from angles just below and just above the horizon. The distribution of photon energies incident from the lower hemisphere clearly shows energies up to about 2 MeV, with distinct peaks of monoenergetic gamma rays. However, only a relatively low energy continuous distribution is incident from the upper hemisphere. The maximum photon intensity in the scattered radiation from the upper hemisphere was found by Mather et al. to be about 75 keV. Frank, in somewhat similar experiments, found an intensity maximum in the photon spectrum at slightly more than 100 keV.

* Note that the angle θ both in Fig. 6 and in the text is measured from the nadir, whereas the angle θ used by both Mather et al. and by Frank is measured from the zenith.

The effect of ground roughness has been determined in these experiments by measurements of the direct component of the radiation. Mather assumes this radiation to have an intensity I (in photons sec^{-1} cm^{-2} $steradian^{-1}$) given in the limited range of angles for which $0^\circ < \theta < 90^\circ$ by $I = S \left\{ \exp \left[-\alpha/\cos \theta \right] \right\} / 4\pi \cos \theta$, in which S is the mean source strength of the distributed fallout in units of photons sec^{-1} cm^{-2}. The parameter α is related to the average attenuation characteristics of the material between source and detector. The values of S for the gamma-ray intensity I were determined from the direct-radiation spectrum, and the values of α were determined from a comparison of the observed distribution of intensities of the direct radiation with that expected from an infinitesimally thin plane source in a vacuum (no absorption or scatter). In both cases the effect of ground roughness could be simulated by assuming a plane source covered by a layer of earth. In the area where Mather et al. made their measurements, the layer of earth amounted to a thickness of 0.45 g/cm^2 plus 106 cm of air, and in the area measured by Frank a thickness of 0.95 g/cm^2 plus 122 cm of air.

Huddleston et al. compared their dose vs. angle of incidence measurements with a calculation by Spencer[44] to determine the effects of ground roughness. They found angular distributions from measurements made three feet above the surface which, when compared with calculations made by Spencer, are comparable to the radiation expected in air about

40 feet above a planar infinitesimally thin source. Further, they found the distribution over a dry-lake bed to closely approximate Spencer's calculated distribution for an air-equivalent distance of 20 feet, and over a plowed field an air-equivalent distance of between 40 and 60 feet.

The equivalent air thickness reported by Huddleston et al. is somewhat greater (if converted to g/cm^2) than the equivalent earth thicknesses reported by Mather et al. and by Frank. The differences may have real significance or they may possibly depend on assumptions made in the calculations. The general conclusions derived from these results are that the use of an equivalent air attenuation to represent the soil attenuation produced by ground roughness effects appears to give results that are in reasonably good agreement with experimental observations.

Concluding Remarks

This discussion provides a brief summary of currently available information about ionizing radiations from fallout. A few references are attached to provide a basis for additional search of the literature. Such a large number of papers have been written on various aspects of the subject that a complete bibliography would be almost impossible for a meeting of this type. However, those references included should provide essentially all information that is needed.

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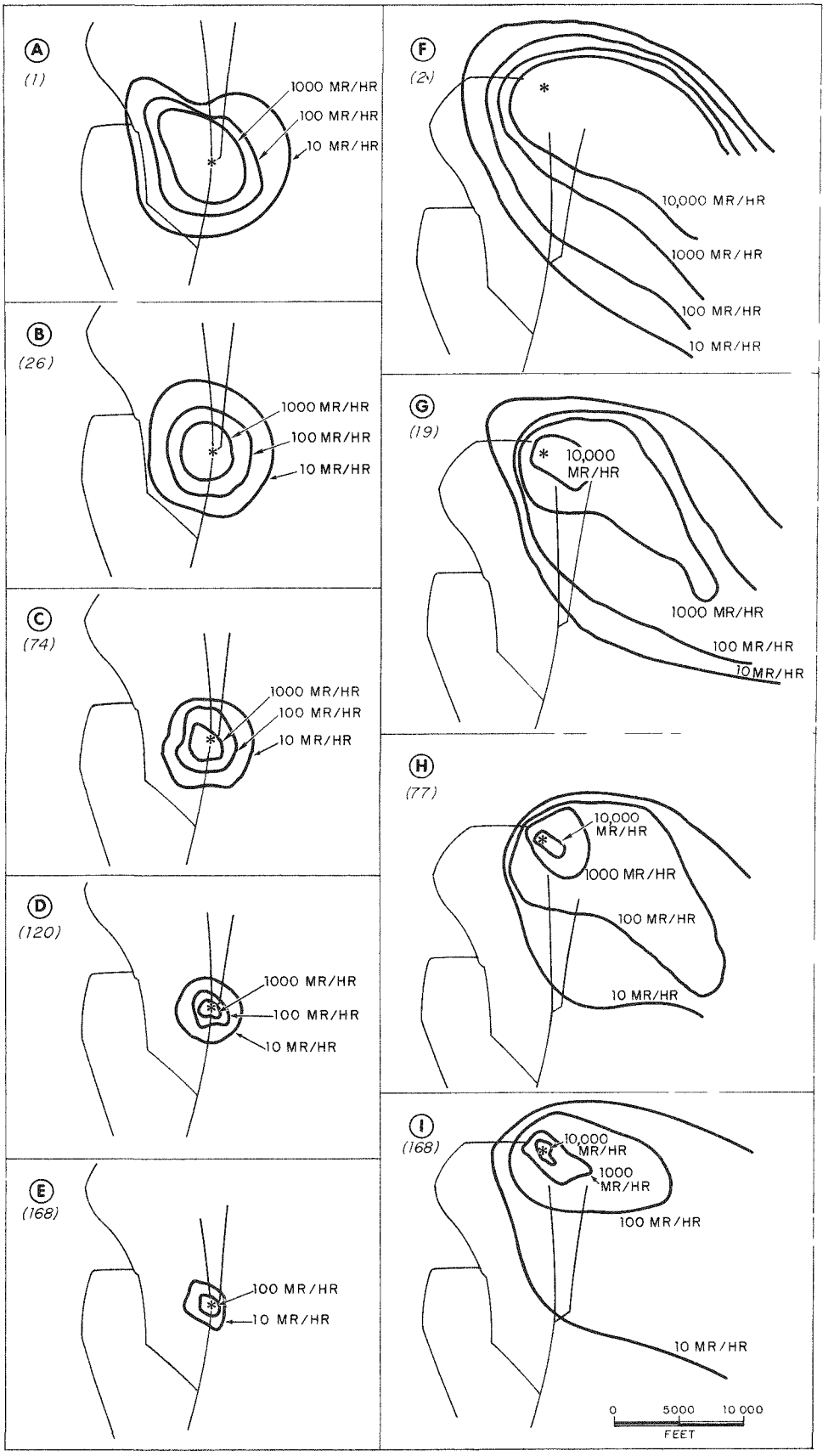
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B
(26)
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C
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100 MR/HR
10 MR/HR
D
(120)
1000 MR/HR
100 MR/HR
10 MR/HR
E
(168)
100 MR/HR
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F
(2)
10,000 MR/HR
1000 MR/HR
100 MR/HR
10 MR/HR
G
(19)
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Fig. 1

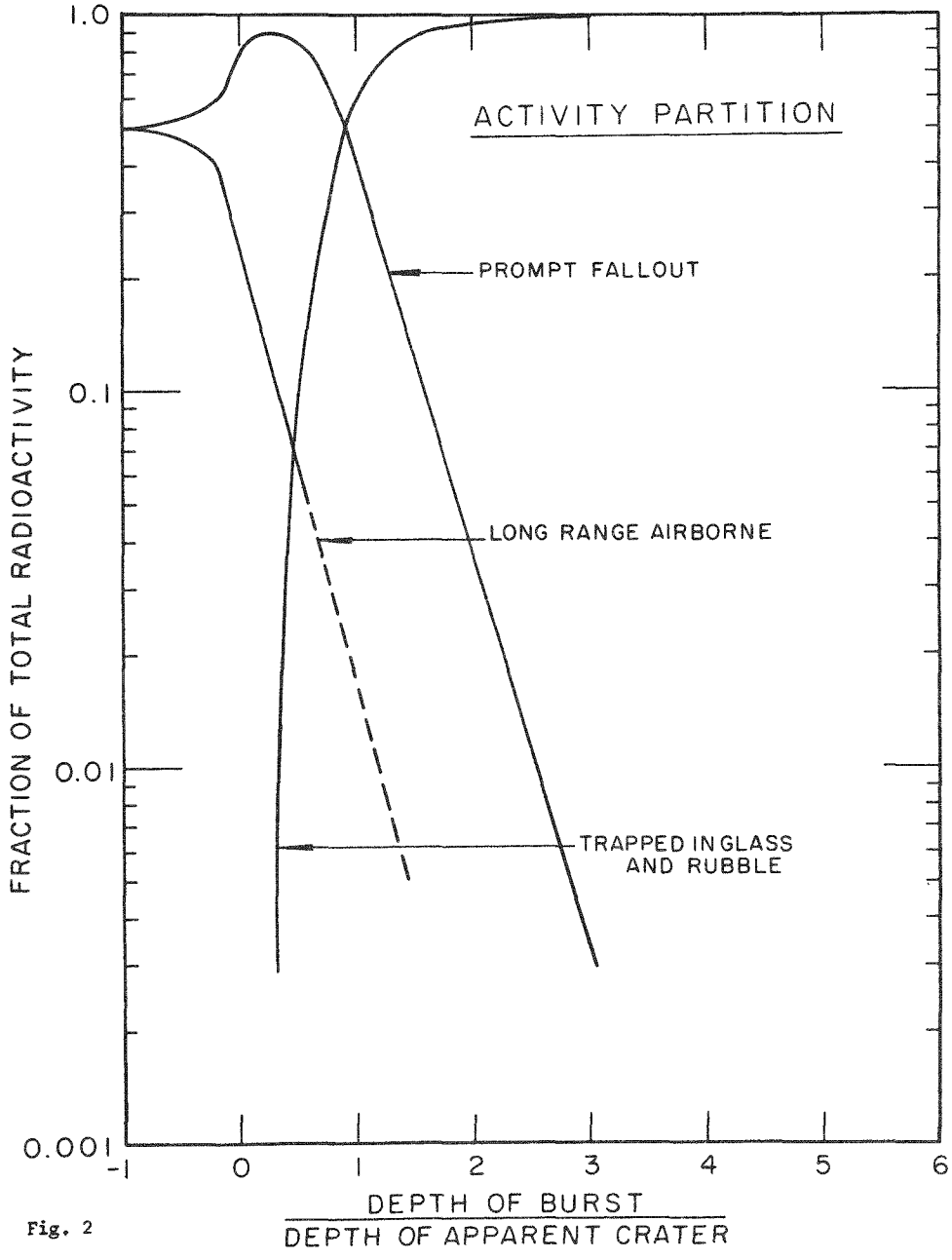

ACTIVITY PARTITION
PROMPT FALLOUT
LONG RANGE AIRBORNE
TRAPPED IN GLASS AND RUBBLE
FRACTION OF TOTAL RADIOACTIVITY
1.0
0.1
0.01
0.001
-1
0
1
2
3
4
5
6
DEPTH OF BURST
DEPTH OF APPARENT CRATER

Fig. 2

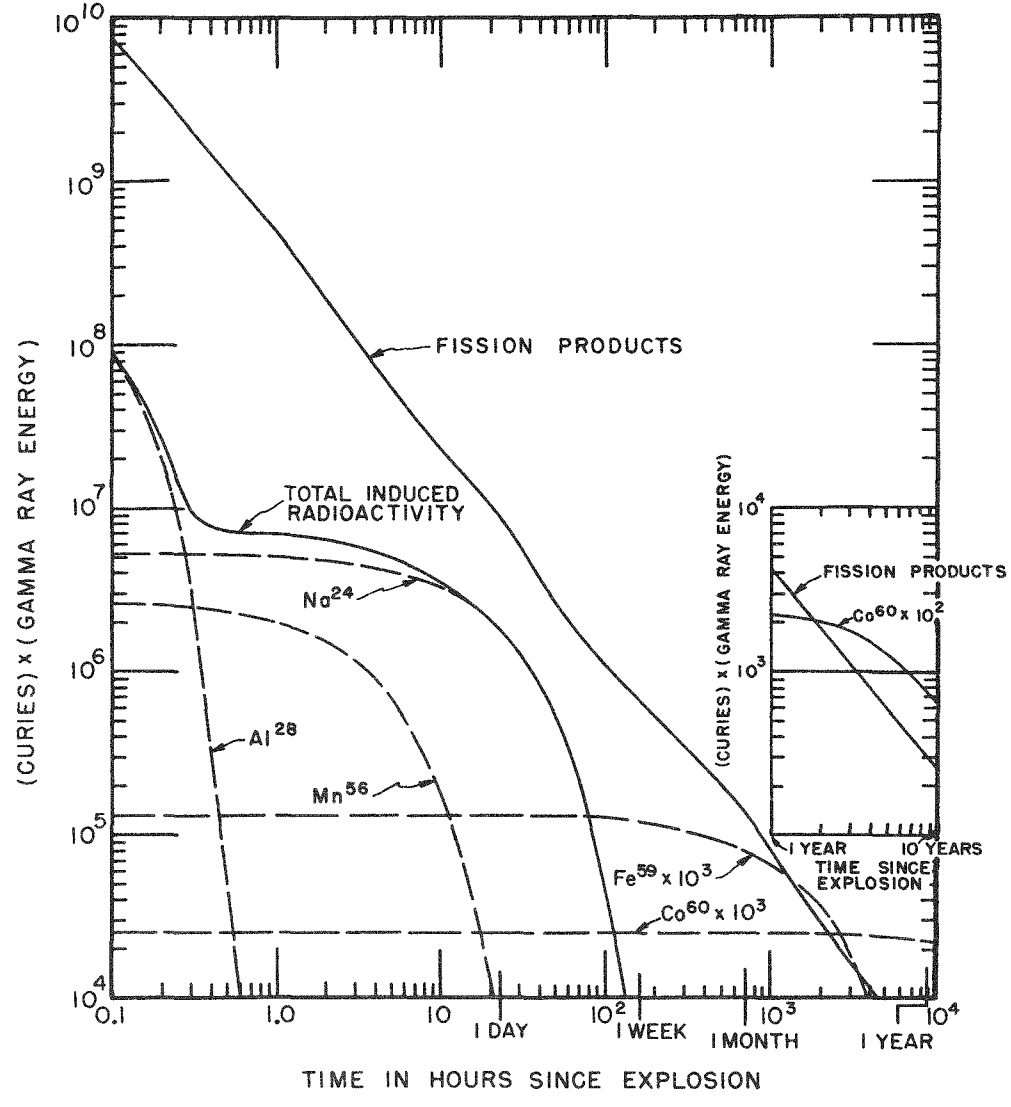
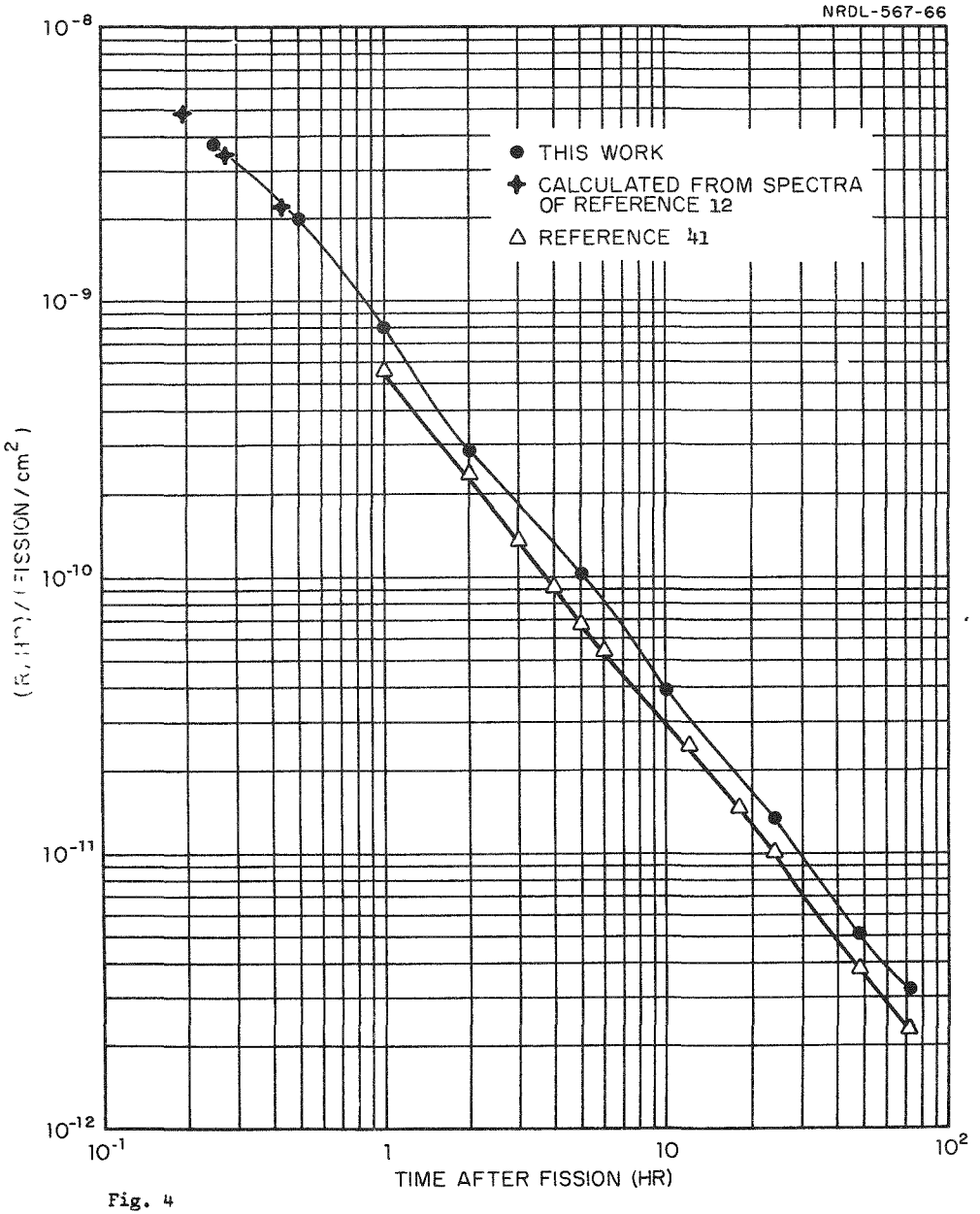

FISSION PRODUCTS
TOTAL INDUCED RADIOACTIVITY
Na24
Al28
Mn56
Fe59 x 10^3
Co60 x 10^3
(CURIES) x (GAMMA RAY ENERGY)
10^10
10^9
10^8
10^7
10^6
10^5
10^4
0.1
1.0
10
1 DAY
10^2
1 WEEK
10^3
1 MONTH
10^4
1 YEAR
TIME IN HOURS SINCE EXPLOSION
FISSION PRODUCTS
Co60 x 10^2
1 YEAR
10 YEARS
TIME SINCE EXPLOSION

Fig. 3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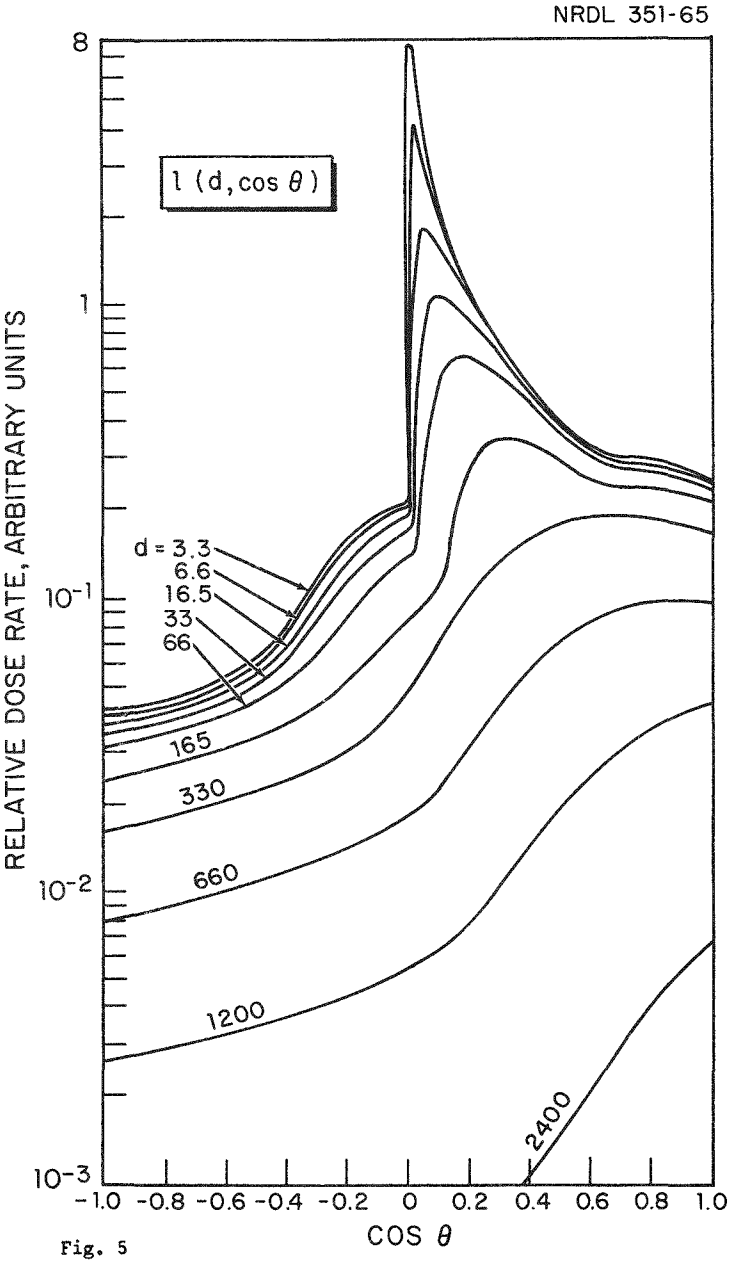
THIS WORK
CALCULATED FROM SPECTRA OF REFERENCE 12
REFERENCE 41
TIME AFTER FISSION (HR)

Fig. 4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l (d, cos θ)
d = 3.3
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165
330
660
1200
2400
RELATIVE DOSE RATE, ARBITRARY UNITS
COS θ

Fig. 5

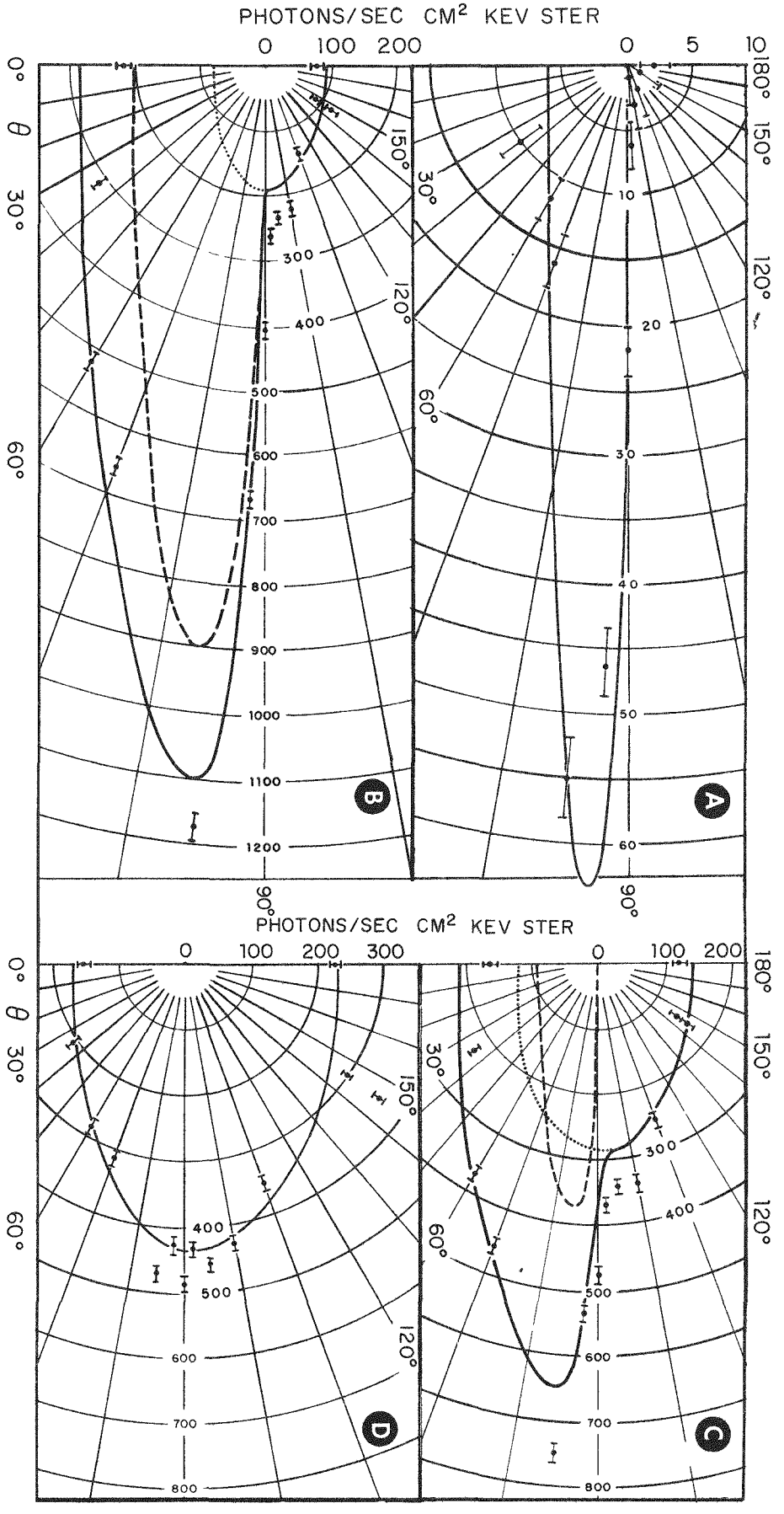
PHOTONS/SEC CM² KEV STER
0 100 200
0 5 10
0° θ 30° 60°
180° 150° 120°
30°
60°
90°
300
400
500
600
700
800
900
1000
1100
1200
10
20
30
40
50
60
B
A
PHOTONS/SEC CM² KEV STER
0 100 200 300
0 100 200
D
G

Fig. 6